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Probing the eV-Mass Range for Solar Axions with CAST

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Abstract—The CERN Axion Solar Telescope (CAST) is searching for solar axions which could be produced in the core of the Sun via the so-called Primakoff effect. Not only would these hypothetical particles solve the strong CP problem, but they are also one of the favored candidates for dark matter. In order to look for axions originating from the Sun, CAST uses a decommissioned LHC prototype magnet. In its 10 m long magnetic field region of 9 Tesla, axions could be reconverted into X-ray photons. Different X-ray detectors are installed on both ends of the magnet, which is mounted on a structure built to follow the Sun during sunrise and sunset for a total of about 3 hours per day. The analysis of the data acquired during the first phase of the experiment with vacuum in the magnetic field region yielded the most restrictive experimental upper limit on the axion-to-photon coupling constant for axion masses up to about 0.02 eV. In order to extend the sensitivity of the experiment to a wider mass range, the CAST experiment continues its search for axions with helium in the magnet bores. In this way it is possible to restore coherence of conversion for larger masses. Changing the pressure of the helium gas enables the experiment to scan different axion masses in the range of up to about 1.2 eV. Especially at high pressures, a precise knowledge of the gas density distribution is crucial to obtain accurate results. In the first part of this second phase of CAST, ⁴He was used and the axion mass region was extended up to 0.39 eV, a part of phase space favored by axion models. In CAST's ongoing ³He phase the studied mass range is now being extended further. In this contribution the final results of CAST's ⁴He phase will be presented and the current status of the ³He run will be given. This includes latest results as well as prospects of future axion experiments.

I. INTRODUCTION

QUANTUM Chromodynamics (QCD) is expected to violate CP-symmetry. Astonishingly, this non-conservation of CP in strong interactions has not been observed by any experiment. In 1977, Roberto Peccei and Helen Quinn [1] formulated a possible solution to the strong CP-problem. They succeeded in explaining the apparent conservation of CP in strong interactions by introducing only one additional

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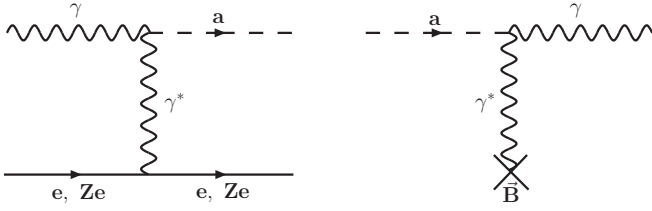


Fig. 1. Left: Feynman diagram of the Primakoff effect expected to occur in the solar core. In the electric field, which originates from the charged particles in the plasma, a photon can convert into an axion. Right: In a laboratory magnetic field the inverse Primakoff effect might take place, i.e. the axion can couple to a virtual photon provided by the transverse magnetic field resulting in a real X-ray photon.

symmetry, which is now referred to as the Peccei-Quinn-symmetry. When this new global symmetry is spontaneously broken at a yet unknown breaking scale f_a , it gives rise to a Goldstone boson as Steven Weinberg and Frank Wilczek [2] pointed out independently in 1978. This neutral pseudo-scalar is generally referred to as the axion. The new particle is especially appealing to researchers since in addition to solving the strong CP-problem, the axion would also provide an excellent candidate for Dark Matter due to its expected physical properties.

II. EXPERIMENTAL AXION SEARCHES

If they exist, axions could have been created in the very early universe. They could also be continually generated in the cores of stars like our Sun. In addition it should be possible to produce the feebly interacting particles in the laboratory by the use of strong magnetic fields and powerful lasers.

Since the breaking scale f_a is not a priori determined, the axion mass is initially unknown. Several constraints from astrophysics and cosmology have been applied in order to prove or rule out the existence of the axion. The mass range, in which axions are still likely to exist, could be narrowed down to a window reaching from μeV up to about 1 eV using the above mentioned constraints along with early experimental results. Several experiments have attempted to detect axions in and close to the remaining mass regions. Although different methods have been applied in the quest for the postulated particle, most of them make use of the so-called Primakoff [3] effect (see Fig. 1), which allows for a conversion of axions into photons in the presence of strong electromagnetic fields [4]. One possible kind of experiment employing this effect are helioscopes [5], ready to detect the signature of axions produced in the closest celestial axion source available: the core of the Sun. Due to the strong electric fields present in the plasma of the solar core, most axions are expected to originate from the inner $\approx 20\%$ of the solar radius as indicated in Fig. 2. One can thus expect a mean energy of these solar axions from Primakoff conversion to be around 4.2 keV. Helioscopes use a strong transverse magnetic field to reconvert solar axions arriving at Earth via the inverse Primakoff effect. They are able to provide a significantly more efficient reconversion of axions than would be possible in crystals, for example. The

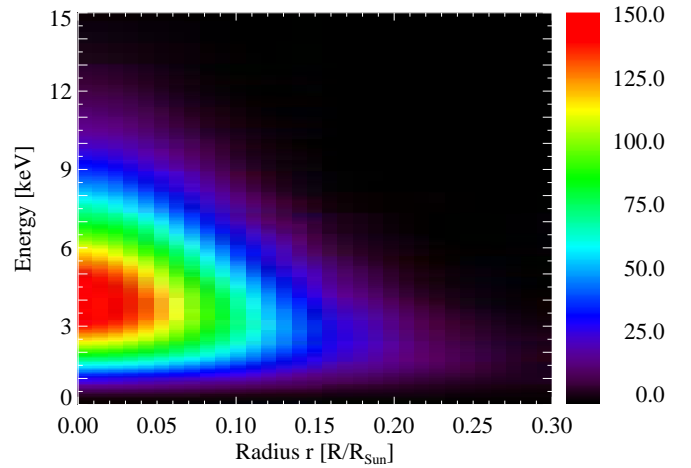


Fig. 2. Contour plot of the axion surface luminosity of the Sun as a function of energy and dimensionless radial coordinate r . The flux is given in units of $\text{axions}/(\text{cm}^2 \cdot \text{s} \cdot \text{keV})$ per unit surface area on the solar disk [6].

resulting X-ray photons can be detected with conventional X-ray detectors. The advantage of this type of axion experiments is the large range of potential axion masses that can be studied with excellent sensitivity.

III. THE CAST EXPERIMENT

The CERN Axion Solar Telescope (CAST, see Fig. 3), which utilizes one of the prototypes of a superconducting LHC dipole magnet providing a magnetic field of up to 9 T, is presently the most sensitive existing helioscope. Due to the way CAST is constructed, the experiment is able to follow the Sun twice a day during sunset and sunrise and thus data can be acquired in axion-sensitive conditions for a total of about 3 h per day. During the remaining time, i.e. when the CAST magnet is not aligned with the solar core, background data is taken. A good knowledge of the background is essential, since the rare event experiment is located above ground. Several X-ray detectors have been

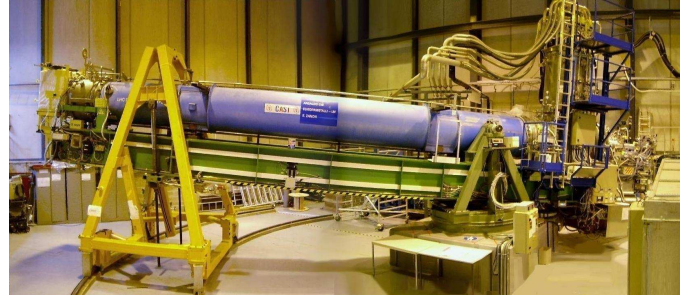


Fig. 3. Experimental setup of the CERN Axion Solar Telescope. The superconducting magnet (blue) is installed on a platform (green), which is supported on the right hand side by a turntable (olive green) allowing horizontal movement. On the other end (left in image), it is carried by two lifting screws at a girder (yellow) for enabling vertical movement. The yellow girder also allows for the horizontal movement along the rails visible on the floor of the experimental hall. Part of the cryogenics plant to cool the superconducting magnet is visible on the right side. The whole setup allows for tracking the Sun twice a day for 1.5 hours each.

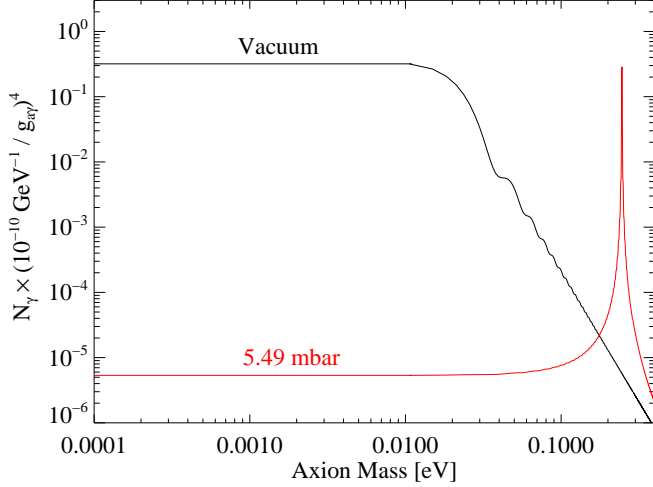


Fig. 4. Expected number of photons from axion-to-photon-conversion for CAST with evacuated magnet bores (Phase I, black). An example for a pressure setting measured during Phase II is shown in red.

mounted at both ends of the 10 m long magnet in order to search for photons from Primakoff conversion. Installed on one end of the dipole, two novel MICROMeSh Gaseous Structure (MICROMEGAS, MM, [7]) detectors search for the signature of axions during sunset. These detectors replaced the formerly used conventional Time Projection Chamber (TPC, [8]) and thus improved the sensitivity of the experiment. On the other side of the solenoid, two further detectors are mounted waiting for an axion signal during sunrise. One of the ports of the dipole is covered by another 2nd generation MICROMEGAS detector, while the other is utilized by an X-ray telescope consisting of a combination of X-ray mirror optics with a Charge Coupled Device (CCD) as a focal plane detector [9]. Both the CCD and the X-ray optics are prototypes developed for X-ray astronomy [10]. By focusing the photons from axion conversion to a small spot on the CCD chip, the X-ray mirror telescope produces an “axion image” of the Sun. This enhances the signal-to-background ratio and in turn improves the sensitivity of the experiment substantially.

In order to investigate different axion mass ranges, the CAST experiment consists of two phases. During the first stage the magnetic field region was evacuated and masses up to 0.02 eV were investigated with very high sensitivity. In order to extend the range towards higher masses, a gas needed to be inserted, restoring the coherence for axion-to-photon conversion (see Fig. 4). For this purpose helium gas was chosen. Since the magnet is operated at 1.8 K, ^4He gas can only be used up to a pressure of 16.4 mbar, a condition at which it liquefies, and in order to continue the search it has to be substituted by ^3He .

IV. PHASE I AND ^4He RESULTS OF CAST

The first phase of CAST concluded in 2004 with two years of data taken. No significant signal above background was observed when following the Sun. Thus, an upper limit on the axion-to-photon coupling of $g_{a\gamma} < 8.8 \times$

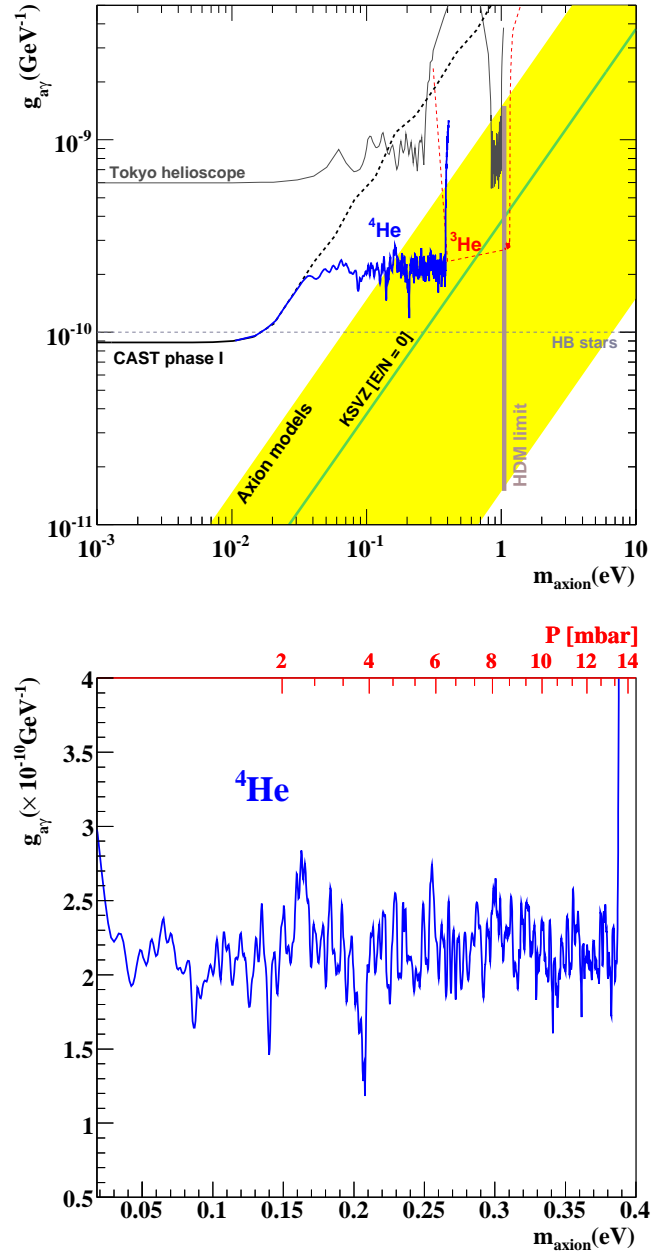


Fig. 5. Top: CAST exclusion plot of the axion-to-photon coupling constant at 95% C.L. for all data obtained in Phase I and Phase II with ^4He gas at CAST with the three X-ray detectors of the experiment (CCD, MM and TPC). The achieved limit of CAST is compared to the latest results of the Tokyo helioscope Sumico [12]. Furthermore, the Horizontal Branch (HB) star limit [13] and the hot dark matter (HDM) limit [14] are included. The yellow band represents the typical theoretical axion models and the green solid line corresponds to the case of the KSVZ model with $E/N = 0$. The prospects for data taking with ^3He have been included in red [11]. Bottom: Expanded view of the ^4He limit for all detectors combined. The upper bound is shown between axion masses of 0.02 eV and 0.39 eV, which corresponds to pressures from 0.08-13.4 mbar.

$10^{-11} \text{ GeV}^{-1}$ (95% C.L.) for axion masses $m_a \lesssim 0.02 \text{ eV}$ was determined and has been published [6]. Following the completion of Phase I, CAST was upgraded to allow for operation with helium gas at various pressures inside the magnetic field region. For this purpose, a sophisticated gas

system and novel cold windows were designed and installed. The main criteria for this gas system were to allow for very accurate and repeatable metering of helium and to prevent any possible loss of ^3He gas.

During the first part of Phase II in 2005 and 2006 the magnet was filled with ^4He gas and axion masses up to 0.39 eV have been investigated by measuring a total of 160 different density steps between 0.08 mbar and 13.4 mbar. A typical upper limit on the axion-to-photon coupling of $g_{a\gamma} \lesssim 2.2 \times 10^{-10} \text{ GeV}^{-1}$ at 95% C.L. for axion masses $m_a \lesssim 0.39 \text{ eV}$ was extracted [11], since no significant excess of X-rays was observed, when the magnet was pointing to the Sun. The exact value of the upper limit depends on the considered pressure setting. The final results for the ^4He data are displayed in Fig. 5 together with the initial prospects for the ^3He run, during which axion masses up to 1.2 eV are being studied.

V. FIRST PRELIMINARY RESULTS OF CAST WITH ^3He

Currently, CAST is taking data with ^3He in the magnet bores. Nearly 700 density steps have already been measured, corresponding to a search for axion masses up to about 0.93 eV. In Fig. 6 a preliminary exclusion plot for the ^3He data acquired during 2008 is shown. It includes data from three out of the four CAST detectors and covers axion masses up to about 0.65 eV. Analysis of the data from the remaining CAST detector is in progress and the final, combined results are expected soon.

Further upgrades of the experiment are underway, including the design, construction and installation of a new frame-store CCD with enhanced performance in comparison to the presently installed detector. Data taking is ongoing with the goal to study axion masses up to $\approx 1.2 \text{ eV}$ by middle of 2011. This corresponds to a maximum pressure of $\approx 120 \text{ mbar}$ (at 1.8 K) for the ^3He gas inside the magnetic field region. Furthermore the collaboration is working towards a near-term extension of the experiment, in which searches for various types of particles will be possible by enhancing the existing apparatus and installing additional components. Among the possible search candidates are standard-QCD axions, chameleons, paraxions and any other WISPs (Weakly Interacting Slim Particles). Beyond these efforts, CAST is also investigating the possibility to build a next-generation axion helioscope (NGAH) in order to achieve at least an order of magnitude higher sensitivity in searching for axions.

VI. CONCLUSION

The results obtained by CAST from the combination of Phase I and Phase II data make CAST the first experiment to search unexplored regions of axion parameters space that are favored by theoretical models. At this time, CAST is thus one of the most sensitive experiments looking for axions over a wide mass range. With ^3He in the magnetic field region, CAST is currently extending its axion search even further into the unexplored regions of the favored axion models and is continuing the quest for the elusive particle. The analysis of these data is ongoing and a first preliminary exclusion plot has

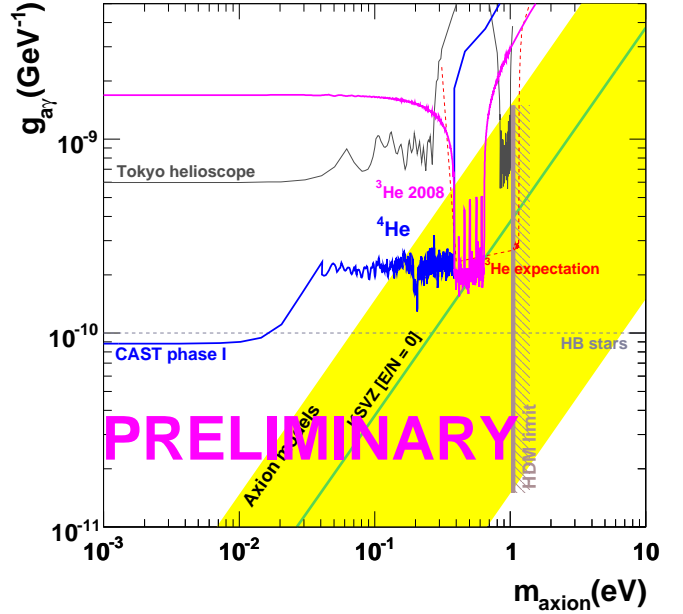


Fig. 6. CAST exclusion plot of the axion-to-photon coupling constant at 95% C.L. for all data obtained in Phase I and Phase II with ^4He and ^3He gas at CAST. The results obtained with ^3He gas in the magnet during the data taking period in 2008 are preliminary. This upper limit takes into account three of the four CAST detectors and covers axion masses from about 0.39 eV to 0.65 eV.

been presented in this paper.

Currently, studies for future axion searches especially using the helioscope technique are under way. Various improvements could increase the discovery potential and lower the existing upper limits on the axion-to-photon coupling constant. On one hand, higher sensitivity can be achieved by employing extremely low background detectors, possibly in combination with X-ray focussing devices, while on the other hand an extension of the exposure time is able to increase the sensitivity of a helioscope experiment. If the movement of the employed magnet can be made more flexible, so that it can be aligned with the Sun for a longer period of time, this exposure time can be significantly increased. A major enhancement of the given sensitivity can however only be obtained by increasing the product of the length and the magnetic field strength, as well as its cross-sectional area. Given present estimates an improvement in the limit on the coupling constant by more than one order of magnitude could be achieved within the coming decades taking into consideration the factors mentioned above. Together with axion haloscopes, which are searching for galactic axions, helioscope experiments could study large parts of the remaining favored model region for QCD axions.

Either way the goal of present and future axion searches remains challenging: the hypothetical particle has to be found or ruled out by closing the allowed mass window once and for all. Experiments such as CAST will certainly shed more light on this particular dark matter candidate, the axion, in the coming decade.

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